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DIASTROPHISM AND THE FORMATIVE PROCESSES

XII. THE PHYSICAL PHASES OF THE PLANETARY NUCLEI DURING THEIR FORMATIVE STAGES

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In an article in the first number of this volume of the *Journal* a study of the relative densities of the moon, Mars, Venus, and the earth brought out the fact that the mean densities of these bodies not only rise in the order of their masses, but that the rate of increase itself rises with each unit-increase of mass.[1] This led to a study of the processes by which these bodies acquired their material, to see whether any part of the observed higher density could reasonably be assigned to greater proportions of inherently heavy material received during their formation. The conclusion was reached that larger proportions of *light* material entered into the formation of the large bodies than into the small bodies. The natural inference from this is that the higher mean densities now found in the larger bodies are due to some form of mass-effect that was sufficient to

[1] "The Order of Magnitude of the Shrinkage of the Earth deduced from Mars, Venus, and the Moon," *Jour. Geol.*, Vol. XXVIII (1920), pp. 1–17. Compare this with the theoretical deductions of Dr. A. C. Lunn, "Geophysical Theory under the Planetesimal Hypothesis, in the Tidal and Other Problems," *Carnegie Institution Publication No. 107* (1909), particularly pp. 188 and 201. Compare also the very suggestive paper of Dr. Wm. D. MacMillan "On Stellar Evolution," *Astrophys. Jour.*, Vol. XLVIII (July, 1918), pp. 36–40.

overbalance their higher content of light original material.[1] It was recognized, however, that the inquiry could not be regarded as having covered all the shrinkage phases of this mass-effect until the physical states of the four bodies during their formation were considered. Under the planetesimal hypothesis their formation embraced two phases: (1) the progressive concentration of those portions of the solar outbursts that were held together by their mutual attractions so as to act as unit assemblages and thus serve as collecting centers or nuclei; (2) the gathering into these nuclei of such scattered parts of the solar outbursts as were dispersed into planetesimal orbits from which they could be picked up only individually. The first process started with a gaseous body and followed the gaseous line of descent; the second was concerned with individual bodies and orbital dynamics. This paper is confined to the first of these.

THE SUCCESSIVE PHYSICAL PHASES ASSUMED BY THE NUCLEI IN PASSING FROM THEIR ORIGINAL CONDITION TO THEIR FINAL STATES AS PLANETARY CORES

There is a wide range between the largest planet and the smallest planetoid. There may also be wide differences of view respecting the probable sizes of the nuclei. As I wish to leave the question of the nuclear masses freely open for the present, it seems best to treat broadly the whole group of solar dependents, including planets, planetoids, and satellites. There is the additional reason that their gradations, their likenesses, and differences, as well as the contrasts of their extreme developments, form the natural background for the special cases with which we are particularly concerned in this discussion.

It is assumed that each one of the present planets, planetoids, and satellites started from a nucleus inherited from a solar outburst. It is held that some of these nuclei were formed from the central portions of the solar outbursts, while others were merely segments detached from these. Some of the detached segments are supposed to have remained under the control of the central portions and become satellites, while others pursued orbits of their

[1] "Selective Segregation of the Earth and Its Neighbors," *Jour. Geol.*, Vol. XXVIII (1920), pp. 126–57.

own and became planetoids. These are regarded as natural results of solar eruptions under exceptional stimulus from a passing body.[1]

As the assigned result of this there arose a very significant series of solar attendants of cognate birth and linked together by gradations, though the extremes were quite highly differentiated. The series, as now presented, ranges from massive hot gaseous planets of low densities, down through intermediary forms, to quite small solid bodies of high densities and altogether devoid of appreciable atmospheres. In mass value the largest planet is several million times the smallest planetoid—probably we could say several billion times, if the lower limit of the planetoids were accurately determined. In Table I this great series is listed in the order of size, neglecting the common distinction between planets, planetoids, and satellites, which is immaterial in this particular study. The physical differences are brought out by groupings. It will be seen that the planets, planetoids, and satellites are notably mixed in the lower part of the list. The gradation would doubtless be much closer and the classes even more intermixed, if the sizes of all the smaller bodies were well enough determined to permit a strictly accurate arrangement of the smaller masses. There are now known to be 26 satellites and upward of 800 planetoids, most of which seem to be less than 100 miles in diameter.

While in general there is a notable gradation, there is yet a wide gap between the giant group of gaseous planets and the terrestrial group next below, which are essentially solid but have gaseous envelopes. Within the latter group a somewhat notable difference in mass sets off the earth and Venus from Mars. The scant atmosphere of the last allies it to the atmosphereless group below and its nucleus not unlikely belonged to that class.

The differences in the groups suggest that the formative processes, though of the same type and initiated in the same way, entered in such different proportions into the actual formative work that they gave rise to very divergent results. This tallies with our earlier suggestions that the formative agencies embraced within

[1] See the special cases of May 29 and July 15, 1919, outlined in this *Journal*, Vol. XXXVIII (February–March, 1920), pp. 145–49, or the original description by Pettit, in *Astrophys. Jour.*, Vol. L (October, 1919), pp. 206–19.

themselves opposing factors (VII of previous article)[1] so poised as to permit a ready shifting of dominance from one side of the

TABLE I

THE SOLAR DEPENDENTS GRADED BY SIZE AND GROUPED BY PHYSICAL PROPERTIES

A. THE GIANT GROUP. HIGHLY GASEOUS BODIES

(Densities low; diameters between 30,000 and 90,000 miles)

	Densities	Diameters in Miles
Jupiter.........	1.25	88,392
Saturn.........	0.63	74,163
Neptune.......	1.09	34,823
Uranus.........	1.44	30,193

B. THE MEDIAL OR TERRESTRIAL GROUP. SOLID BODIES BEARING ATMOSPHERES

(Densities high; diameters between 4,000 and 8,000 miles)

	Densities	Diameters in Miles
Earth..........	5.53	7,918
Venus..........	4.85	7,701
Mars...........	3.58	4,339

C. THE DIMINUTIVE GROUP. ATMOSPHERELESS SOLID BODIES

(Densities high; diameters ranging from 3,600 miles down to the lower limit of estimating power)

	Bodies	Diameters in Miles
Satellite..	Jupiter's III	3,558
Satellite..	Jupiter's IV	3,345
Planet...	Mercury	3,009
Satellite..	Saturn's VI	3,000

THE DIMINUTIVE GROUP—*Continued*

	Bodies	Diameters in Miles
Satellite..	Jupiter's I	2,452
Satellite..	The Moon	2,100
Satellite..	Jupiter's II	2,095
Satellite..	Saturn's VIII	2,000
Satellite..	Neptune's VIII	2,000
Satellite..	Saturn's V	1,500
Satellite..	Saturn's III	1,200
Satellite..	Saturn's IV	1,100
Satellite..	Uranus's I–IV	500 to 1,000
Satellite..	Saturn's II	800
Satellite..	Saturn's I	600
Satellite..	Saturn's VII	500
Planetoid	Ceres	485
Planetoid	Pallas	304
Planetoid	Vesta	243
Satellite..	Saturn's IX	200
Planetoid	Juno	118
Planetoid	Several exceeding	100
Satellite..	Jupiter's I	100
Planetoids	Probably 700 or more, ranging downward from	100
Satellite..	Mars's II	...
Satellite..	Mars's I	10
Satellite..	Jupiter's VI and VII	"small"
Satellite..	Jupiter's VIII and IX	"very small"

Planetoids. The smallest order of planetoids probably form the lower end of the series, ranging down to 10 or perhaps even 5 miles.

balance to the other, thus giving rise to a series of widely varying effects which at the extremes even became contrasted. The preponderance in the upper end of the series lay markedly on the

[1] "Selective Segregation of Material in the Formation of the Earth and Its Neighbors," *Jour. Geol.*, Vol. XXVIII (1920), pp. 126–57.

side of gas accumulation, while in the lower part the dominant effect lay in the dissipation of all gas. In the middle ranges there was a closer approach to equipoise between these extremes and hence to a mixed product of the medial order. It is thus clear that the genetic processes, however alike basally, were capable of giving such different results as to make it necessary to study with care and patience the balancings between opposing influences and the differential effects of the shifting of these balances.

THE CRITICAL CONDITIONS THAT CONTROLLED THE PASSAGE OF THE NUCLEI INTO COLLECTING CORES

The original diversity of the nuclei is assigned to differences in the impulses imparted by the solar eruptions. The evolution of the nuclei, after being launched on their several careers, was critically dependent on the dynamic properties which they inherited individually. These now require attention. We need not dwell, however, on the giant gaseous planets, for they do not fall within the range of our present problem, nor do they seem to have ever passed through the more critical phases of the processes we are about to consider. They probably had, at the outset, nuclei massive enough to hold essentially all their own gases in spite of their molecular activity and to retain essentially all alien molecules that plunged into them.[1]

To cover the whole field of the known solid bodies in a representative way, Table II is introduced. It gives certain essential dynamic properties for ten typical bodies, four natural and six ideal, so selected as to represent at convenient intervals the whole range from the earth—the largest known solid body—down to a ten-mile planetoid. Dr. W. D. MacMillan has been kind enough to make the computations for this table.

It seems improbable that the nuclei of the earth, Venus, Mars, or the moon, even at their smallest stages, were so diminutive as the lower orders of ideal bodies in Table II, but these very small bodies are even more serviceable than larger ones in illustrating the critical conditions that attended their formation and measurably that of

[1] The inevitable loss of such molecules as attained very exceptional speeds is neglected throughout this discussion.

the larger bodies of the solid order. They thus serve to put to severe test our notions as to the formation of such bodies. It will not be surprising if we find that these small bodies lie on the precarious border that separates successful aggregation from dissipation into planetesimals.

TABLE II

DYNAMICAL PROPERTIES OF TEN REPRESENTATIVE BODIES OF THE TERRESTRIAL AND SMALLER CLASSES

THE TEN BODIES		STATISTICAL PROPERTIES			DYNAMICAL PROPERTIES			
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*
No.	Name	Diam. in Miles	Density Water = 1	Mass Earth = 1	Surface Gravity g = 1	Parabolic Velocity in Miles per Sec.	Velocity of Retention in Miles per Sec.	Diameter of Sphere of Control
I.	Earth	7918	5.53	1.0000	1.00	6.95	4.91	1,240,000
II.	Venus	7701	4.85?	0.807?	0.85	6.33	4.48	1,156,000 (836,000)
III. . . .	Mars	4339	3.58	0.1065	0.36	3.06	2.16	588,000 (898,000)
IV.	Ideal	3407	3.50	0.050	0.27	2.38	1.68	458,000
V	Moon	2160	3.34	0.0122	0.16	1.47	1.04	286,000 (50,000)
VI.	Ideal	1000	3.30	0.001202	0.075	0.68	0.48	132,000
VII . . .	Ideal	500	(*a*) 3.30	0.0001503	0.0375	0.34	0.24	66,000
			(*b*) 5.00	0.000228	0.057	0.42	0.30	76,000
VIII. . .	Ideal	100	(*a*) 3.30	0.000001202	0.0075	0.068	0.048	13,200
			(*b*) 6.00	0.000002186	0.0137	0.123	0.087	16,000
IX. . . .	Ideal	50	(*a*) 3.30	0.0000001503	0.00375	0.034	0.024	6,600
			(*b*) 6.50	0.0000002960	0.0074	0.067	0.047	8,200
X.	Ideal	10	(*a*) 3.30	1.202×10^{-9}	0.00075	0.0068	0.0048	1,320
			(*b*) 7.00	2.550×10^{-9}	0.00160	0.0144	0.0102	1,700

The selections are adapted to the earth as unit and the spheres of control are based on the earth's distance from the sun. An ideal body $\frac{1}{20}$ the mass of the earth is introduced between Mars and the moon to better grade the series, and for a like reason an ideal body 1,000 miles in diameter is introduced below the moon. The four ideal bodies, 500, 100, 50, and 10 miles in diameter, respectively, are selected to cover the range of the planetoids and smaller satellites. The largest of planetoids thus far measured satisfactorily is 485 miles in diameter (Barnard). Two hypothetical densities are assigned to each of these, the one to represent bodies supposed to be composed largely of stony matter, the other to represent those that may have a notable content

of iron. In the 10-mile body this higher density is put at 7, which is thought to be as dense as any such natural aggregate, inevitably more or less mixed and porous, would be likely to be.

Column *f* gives the maximum acceleration of gravity at the surface of the given body, stated in percentages of the acceleration of gravity at the surface of the earth. Column *g* gives, in miles per second, the parabolic velocity (= velocity required to give to a projected body a parabolic path = velocity capable of carrying a body to infinity = velocity acquired in a free fall from infinity = "velocity from infinity"). In discussions of the limitations of atmospheres, this "velocity from infinity" has very commonly been used erroneously as "the critical velocity of escape," but by referring to column *i* it will be seen that a molecule shot away from these bodies may reach the limit of the body's control very much short of an infinite distance. If one wishes to show that the molecules *must escape*, and desires to make his statement conservative by leaving a good "margin of safety" to cover defects in data and otherwise, the parabolic velocity is a very suitable criterion to use. If, on the other hand, one wishes to show that molecules *will be retained*, and desires, as before, to leave a margin of safety for retention somewhat above that, the figures in column *h* form convenient criteria. Strictly speaking, these represent the velocity required to give a particle a circular orbit at the surface of the body, and this velocity forms a dividing line between the ordinary collisional atmosphere and the orbital ultra-atmosphere. The latter forms the transition stage through which molecules may escape from control with the least velocity. The velocity in a circular orbit has a fixed ratio to the parabolic velocity for the same point, viz., $1:\sqrt{2}$. The figures for the parabolic velocity and for the velocity of circular orbit or "velocity of retention" each becomes lower as the points of reckoning rise above the surface. The minimum velocities required for escape lie between the velocity for circular orbit and the velocity of fall from the limit of the sphere of control and are dependent on the mode of escape.

Column *i* gives the diameters of the spheres of control of the several bodies in competition with the sun *at the earth's distance*. It is important to note the qualifying clause, for spheres of control vary with the distance from the controlling body. The *actual* spheres of control of Venus and Mars are given in parenthesis. For the present discussion spheres of control at the distance of the earth are most serviceable. In the case of the moon, the figure in parenthesis represents the moon's sphere of control *as against the earth*, within whose sphere of control it revolves.

It is worthy of note that the spheres of control at the lower end of the series, notwithstanding their diminution, still have notable dimensions. These spheres of control give concrete pictures of the areas over which the several bodies exercise collecting as well as holding power, while the figures in columns *g* and *h* give data for realizing, in terms of velocity, how limited is the power of this influence in the smaller masses.

The table would be additionally helpful if the central pressures, the central densities, and the central temperatures could each be given in terms equally trustworthy, but determinations of these properties rest on a much less secure basis. The central pressures can only be determined by assuming some law of downward increase of internal density. The actual rate of such increase is uncertain, beyond the fact that it must fall within certain rather broad limits defined by precession and other astronomical phenomena whose requirements are not precisely determinable. Laplace's theoretical law of density is perhaps the most plausible and is the one commonly used in preference to such others as have been proposed. Using it, MacMillan finds the central pressure of the 10-mile body, when assigned a mean density 3.30, to be only 11.8 lbs. per square inch, i.e., less than the pressure of the earth's atmosphere. On the other hand, that of the present earth is 22,500 *tons* per square inch, or about 3,000,000 atmospheres. The results given by Laplace's law are in general accord with those obtained earlier in this discussion from a comparison of the moon, Mars, Venus, and the earth.[1] However, reserve in placing implicit confidence in this law is to be observed, for by carrying the series of determinations upward from the earth on the same basis, MacMillan finds that at a radius of about 5,000 miles the central density becomes infinite. This seems to mean either that the law breaks down or else is rendered inapplicable by some intercurrent factor whose nature is as yet unknown. Dr. A. C. Lunn reached results of similar import in his geophysical studies under the planetesimal hypothesis in 1909.[2] The suggestive correlation of the densities of the whole series of planets made by MacMillan in his paper "On Stellar Evolution" deserves thoughtful consideration in this connection.[3]

It is clear, then, that until some elucidation is found for this singular result so shortly reached after the dimensions of the earth are passed, it is unsafe to build important conclusions upon the law.

[1] "The Order of Magnitude of the Shrinkage of the Earth Deduced from Mars, Venus, and the Moon," *Jour. Geol.*, Vol. XXVIII (1920), pp. 1–17.

[2] "The Tidal and Other Problems," *Carnegie Publication No. 107* (1909), pp. 201–2.

[3] *Astrophys. Jour.*, Vol. XLVIII (July, 1918), pp. 36–40.

In reaching conclusions respecting the central temperature there is not only the danger of error due to deducing it from compression computed according to this doubtful law, but there are other sources of uncertainty, among which one of the more serious is the unknown amount of heat removed by inherited eversive movements within the body, co-operating with ordinary convection while the formative processes were in progress, and since. In the distinctly large bodies these might not perhaps rise to decisive value, but in the smaller orders of bodies the central temperature theoretically assignable to concentration might be so far dissipated by the combined effects of inherited eversive movements, convection, conduction, and viselike mechanical action (discussed below) that it would have but limited effect on the physical state of the core into which the nucleus passed.

A further serious difficulty in estimating central temperature arises from our ignorance of what part of the potential energy theoretically set free by compression went into endothermal reorganizations, what part became latent in forming solutions, what part was carried surfaceward by the forced ascent of these solutions, and what remained to increase the temperature.

THE GROUP OF FACTORS THAT CONDITIONED THE PROCESS OF NUCLEAR CONCENTRATION

The passage of the planetary nuclei from their original states as solar gases into their final states as the cores of planets, planetoids, and satellites was by no means so simple a process as gaseous condensation has usually been regarded. Beside the simple condensing process, as usually considered, there were co-operating activities that radically modified the general tenor of the process. Four of these require consideration:

I. *Several types of motion were inherited from the solar eruption, and these took the lead in determining the internal circulation. The thermal convection, as it arose, was superposed on these.*

II. *A sifting of the mixed molecules of the original gaseous matter set in almost as soon as it emerged from the sun and changed the mixture to the proper proportions for forming planetary cores.*

III. *The formation of precipitates also set in early, and gradually changed the primitive gases into Brownian mixtures which themselves*

changed as time went on. In the smallest order of bodies this precipitation, together with the escape of such molecules as remained free, went so far ultimately that the residues were reduced to clouds of precipitates which condensed in a way of their own.

IV. *Almost as soon as cores began to form, differential stresses, more intense below than above, were brought to bear upon them by external agencies which aided in working the lighter and more mobile materials toward the surface, thus developing increasing density and solidity in the central parts.*

In discussing these co-operating factors it will be helpful to have in mind concrete pictures of the deployment of the matter under study, fashioned in the form of spheres of control, for these best bring out the dynamics of the organizing work. The matter in spheres of control may be very differently distributed, but it is to be regarded as occupying in some measure, however scant, the whole space. In adult organizations, usually the matter is highly concentrated toward the center and very sparsely distributed in the outer part. In the initial stages the distribution is likely to be heterogeneous with less difference between the outer and inner parts. Uniform distribution therefore becomes the most convenient standard of reference, though probably never realized in fact. Table II gives data from which selections may be made at pleasure in forming representative pictures.

The primitive earth-mass, before sifting began, should have included (1) the light gases that later escaped and were never recovered, (2) the planetesimals that temporarily escaped and were later recovered, (3) the nuclear portion that remained under self-control, and (4) minor factors that may be neglected. Let the whole be taken as having a mass about twice that of the present earth, without prejudice to a higher or lower final estimate. It would then, if properly distributed, have a sphere of control of the order of 1,500,000 miles in diameter and a mean density for the whole sphere of about 0.0011 on the air standard, or, let us say, approximately 1/1,000 of the density of the air at sea-level. As loss by sifting went on the sphere of control should have shrunk to a minimum, after which, when planetesimal accretion began to

overmatch the molecular escape, it should have grown to its present size. It is not best just yet to try to decide what this minimum may have been, but let it be placed as low as $\frac{1}{10}$ of the present mass of the earth to make the gap between our two pictures wide. Its sphere of control would then have approached 500,000 miles in diameter and the mean density for the whole sphere 0011, on the air standard. The spheres of control are here computed on the supposition that the matter in each case is distributed in spherical form and that each concentric layer is homogeneous. Actual spheres of control are not strictly spherical and the distribution of matter at least in the early stages was probably not homogeneous. The figures given are themselves only convenient approximations, but they serve well enough to indicate the general order of tenuity. Only gravitative attraction is taken into account. The phenomena of comets' heads imply that there is a supplementary force in such very diffuse bodies, perhaps electromagnetic, but that may be regarded as merely a "margin of safety" in this discussion.

Among the points to be noted, though they cannot be discussed here, are: (1) the high degree of tenuity, which gives some notion of the extent to which matter may control itself in the terrestrial part of the solar domain; (2) the temperature produced by the expansion of the solar gases to this degree of tenuity; (3) the facilities for radiation afforded by this tenuity; (4) the nature of the internal movements in such tenuous bodies.

I. *The motions inherited from the solar eruption and their co-operation with convection in modifying the condensation of the nuclei.*— The gaseous matter erupted from the sun inevitably carried into its new activities some measure of the turbulence that previously affected it, while the forces of ejection added to this their own differential impulses. In so far as these impulses had uniform effects on all parts of the erupted mass, they merely served to send the whole out into its orbital course. This does not specially concern us here, but we may note in passing that the uniform increments of motion discovered by Pettit in the solar eruptions of May 29 and July 15, 1919, seem to be singularly felicitous factors in promoting projection into orbits without those high tendencies

to dispersion naturally assigned to simple explosion and that would be unfavorable to self-control.[1] We are here concerned only with those differential impulses that affected the relations of one part of an ejected mass to other parts. It is assumed that these differential impulses were so graded that (1) they scattered into planetesimals a notable part of the projected mass, (2) they tore away from the central portions segments that were massive enough to hold themselves together, but not very firmly, while (3) the main central masses retained a higher degree of self-control.[2] Such a partition of effects seems the natural result of the mechanics of eruption. It seems also to fit the requirements of the bodies that now make up the planetary system. The masses that retained their self-control were the nuclei of the organizations that were to follow, and constitute the theme to which we are here confined.

Under such a range of impulses the nuclei probably graded from the largest and most strongly held down to small diffuse ones on the very limit of self-control, beyond which complete dissipation into planetesimals set in. They are therefore to be dealt with as a graded series rather than a single type. The question of control, however, was not so much a matter of mass as of balance between the force of gravity and of the motions involved.

Three types of inherited motions need recognition: the turbulent, the vortical, and the rotatory. Turbulent motions were not only inherited directly from the sun, but must have been generated by unbalanced thrusts and drags incident to eruption. Eruptive actions almost inevitably give rise to more or less of vortical motion, or at least some form of eversive motion. In free interplanetary space, and in such tenuous bodies as those under discussion, motions of this type might persist long and be specially effective in discharging internal heat. All unbalanced differences of thrust and drag in the ejection of erupted masses would ultimately appear in the form of rotation and so rotation of some order could scarcely have failed

[1] *Jour. Geol.*, Vol. XXVIII (February–March, 1920), pp. 145–49, or the original article by Pettit, *Astrophys. Jour.*, Vol. L (October, 1919), pp. 206–19.

[2] In addition, the least projected parts fell back to the sun, while doubtless some particular parts received cumulative impulses and were thrown into anomalous courses, but these are neglected throughout this discussion.

to be inherited from the ejection. The amount of this primitive rotation, however, is not deducible directly from such rotations as the bodies now have, for the present rotations are assignable chiefly to the effects of planetesimal infall after the nuclei had become planetary cores. This later effect was conformable to a law of equilibrium under which the rotations were sometimes accelerated and sometimes retarded.[1]

When these inherited motions were strong enough to cause dissipation, the nuclei of course vanished into planetesimals, but when they were mild enough to be consistent with control, they became vital factors in the process of concentration. The normal system of thermal convection was gradually developed later and hence had to conform to the inherited motions already in control of the matter. In large nuclei the convectional motions might come in time to dominate the inherited motions, but in the smaller diffuse nuclei that were more quickly cooled it perhaps never came to be more than a secondary factor. At any rate, the dependence of the convective circulation on the inherited motions—merged mainly into rotation later—must have given rise to a distinctly gyratory system of circulation. This doubtless had some analogies with the circulations of the atmosphere and of the ocean, which, though essentially thermal, are profoundly affected by the earth's rotation. A fundamental difference, however, needs notice. We are here dealing with hot bodies whose radiation is primary. The surface of a rotating body has its greatest convexity transverse to the equator, while the polar surfaces are relatively flat. The greatest radiation in proportion to the immediate submass therefore takes place in the equatorial region. In addition to this the escape of molecules is aided by the centrifugal component of rotation, which is greatest at the equator and sinks to zero at the poles.

It has already been noted that escaping molecules carry off thermal energy in relatively high amounts. The escape of molecules may then be regarded as a form of quasi-radiation. It is, therefore, a rather firm inference that the equatorial belt is the most effective cooling tract of a hot, rotating body, though this may easily be masked by the high radiation from all surfaces.

[1] *The Origin of the Earth* (1916), p. 99.

It is a notable fact that the equatorial belts of the sun, Jupiter, and Saturn rotate faster than portions of their surfaces on the same meridian in higher latitudes. This has been the subject of much speculation and has received different explanations, more than one of which may contain a measure of truth. One suggestion is that it is due to the infall of planetesimal matter. A closely allied suggestion is that it is due to the falling back of matter ejected from the sun into the planetary regions and drawn forward in the direction of their motion, so that on returning it carries surplus momentum acquired from the planets. These are not inconsistent with the suggestion here made that part of the acceleration may be merely a phase of circulation normally set up in such hot rotating gaseous bodies. In a hot fluid body of the volume and rate of rotation of the earth, a mass, cooling and sinking from the equatorial surface, would—if it were free from contacts with surrounding matter—acquire an orbital velocity before it reached the center, and hence would sink no farther because the centrifugal component of its motion would wholly offset the pull of gravity upon it. If forced below that depth, its centrifugal component would act as a buoyant force. Of course, the sinking mass never would be free from contacts, and so it would necessarily exchange energies with the contact matter. The sinking mass would thus act as an accelerating undertow for any matter that flowed in above it as it sank; so also it would tend to drag forward whatever was in contact with it on its sides and below. It is not difficult to work out a system of circulation actuated by such equatorial cooling and sinking. It would, however, undoubtedly be subordinate to the intimate turbulence that would spring from other factors. The axial tract would present a unique problem, for it would be little affected by rotation and would not directly be reached by the descending equatorial currents, for they would be restrained by the centrifugal component of rotation and turned northward and southward, completing their circuits by return from the higher latitudes with such deflections as rotation imposed. This part of the circulation may be pictured as two vortex rings made up of spiral submovements trending downward on their contact sides at the equator and upward on their poleward sides. The axial tracts in themselves

would seem to invite a more direct and simple convection, but they might be specially subject to influence from the inherited motions. For example, if the rotation were west-east, like the sun's rotation in which the mass participated before ejection, and there were a north-south axial movement as in the case of the eruptions of May 29 and July 15, 1919, cited above, there might naturally be inherited from this an axial movement from one pole through the center to the other. The original tenuous state would apparently be favorable to this, and, once established, it might be perpetuated as an effective form of central convection. A special interest attaches to this from its possible influence on the solid core as that gradually formed—but this cannot be discussed here.

The point to be emphasized is the inevitable subordination—in the early formative stages—of the convection actuated by difference of temperature to the inherited motions. The circulation, far from being simple descent and ascent, was tortuous and involved, and the core-forming process must be interpreted on this basis.

II. *The molecular sifting of the nuclei required to reduce the original solar gases to the composition of the present solid bodies.*—The nuclei of the giant planets may be passed by, merely remarking that there is little reason to think they suffered much sifting; rather they seem to have been so massive from the outset that they retained all classes of molecules that came under their control. By far the larger number of the solid bodies of the solar system, however, are practically devoid of free gases, and seem to be formed almost wholly of stony and metallic matter. None of the terrestrial planets carry more than a very small percentage of free gases; apparently almost their whole substance consists of stony and metallic materials such as make up the main body of the earth and of meteorites.

The original gases of all the bodies derived from the sun, large and small alike, should have had essentially the same composition. Spectroscopic analysis shows that the visible substance of the sun is an intimate mixture of many kinds of molecules. Unfortunately, their relative proportions can merely be inferred in a general way. The low density of the sun (1.40), notwithstanding its great mass, implies—even when its high temperature is considered—

that the lighter elements form a notable factor, and the spectroscopic evidence tallies with this. The low densities of the giant planets derived from the sun (Jupiter, 1.25; Saturn, 0.63; Uranus, 1.44; Neptune, 1.09) suggest a similar constitution with even more cogency, for they are much less affected by high temperature. If, therefore, solid stony or metallic bodies of high specific gravity were to be formed from outbursts of solar gases, the process must have involved the removal of large quantities of the lighter order of constituents. This sifting is precisely what the kinetic theory of gases applied to small bodies would lead us to expect. The process is essentially a form of evaporation, and so the planetoids and satellites, as well as the terrestrial planets with slight qualification, may be regarded *as merely the residues of the selective evaporation of much larger original bodies of mixed gases.*

If the original gases, after they were projected from the sun, occupied some large part of the spheres they could control, as indicated above, the escape of the lighter molecules would be relatively easy and prompt, at least from the smaller masses. If the nuclei became much condensed before the sifting was completed, the remaining escape might be slow, for the molecules could then only escape from the outer zone where free paths were open to them when they chanced to rebound in an outward direction with the requisite velocity. In so far as the original gaseous masses were affected by turbulence, or by vortical or other eversive motions derived from their ejection, the escape of the light molecules would be facilitated.

The motions inherited from the original expulsion were probably such that the dominant tendency, in all but the more massive nuclei, was toward gaseous dispersion. Not only would the light molecules be likely to escape from control, but many of all kinds. This is only another form of stating the primary tenet of the planetesimal hypothesis, viz., that such dispersion was an inevitable effect of the solar eruptions, and a condition precedent to planetesimal accretion later. There is merely the reservation that enough material was held under self-control to serve as collecting centers of the requisite orders of efficiency, but even this is not essential to an ultra type of planetesimal genesis. It seems, how-

ever, to be definitely implied by a posteriori reasoning from the existing bodies. The present line of attack shows that the nuclei, except the four of the giant order, were little more than the residues of the heavier material left by selective molecular action working on larger original bodies of mixed gases. This seems to apply to all satellites, to all planetoids, and, in qualified degrees, to all planets from the earth downward.

The process of evaporation had the effect of reducing the energy of the residue per unit mass, and this, added to the inevitable loss by radiation, made control increasingly secure and caused loss to diminish till it became negligible.

III. *The formation of precipitates and of Brownian mixtures, grading into quasi-gaseous clouds of precipitate aggregates.*—As the original mixed gases emerged from the sun, expansion, abetted by radiation, must have promptly lowered the temperature, and this lowering of temperature doubtless led to the formation of precipitates. It is immaterial just here whether these precipitates were formed by simple cooling or by chemical action, or by both acting jointly. Nor is it of critical importance whether the precipitated particles were liquid or solid. It is highly probable that the earliest precipitates were formed of material such as later became the stony and metallic substances of the earth, of meteorites, and probably of all the small solid bodies. That such precipitates had begun to form even earlier is highly probable, for they are apparently now forming in the sun; at least the solar photosphere is commonly interpreted as a cloudlike zone of such precipitates.

At the outset such precipitates would necessarily be minute and diffusely scattered, for under the law of diffusion of gases the particular molecules that were precipitable at the temperatures existent at that particular stage would be distributed sub-uniformly throughout the turbulent mixture of molecules which formed the gaseous mass, but aggregation into granules, chondrules,[1] or other forms of concretions would doubtless at once ensue, after the analogy of the droplets and crystals of clouds.

[1] I venture to name chondrules here to suggest that conditions such as these are perhaps those most likely to have given rise to these singular little aggregates found in the majority of meteorites. They are commonly of the size of a millet seed, but range up to that of a walnut and down to dustlike fineness.

The minute precipitates thus scattered through the gas would serve as Brownian particles, and the increase of these would form a progressive series of Brownian mixtures. The minute precipitates would be jostled to and fro much as the free molecules were, except that, on account of their greater sizes and masses, they must have responded rather to combined molecular impacts than to single ones, while their lack of perfect elasticity must also have somewhat toned down these activities.

An analysis of the conditions makes it clear that the Brownian evolution probably diverged very soon into two rather distinct lines, though they must have been united by numerous intermediate phases. One of these may be regarded as the typal line of gaseous descent; the other as divergent toward an alien type that combined a quasi-gaseous phase with a partially orbital factor. In the first the characteristic feature continued throughout to be that of a jostling assemblage, though the original high proportion of molecules gave place more and more to precipitates acting as Brownian particles. The gas in this case is presumed to have passed into the liquid phase and thence into the solid form. In the more divergent line the assemblage lost its free molecules largely, and in the extreme cases entirely, and became at best merely quasi-gaseous, with a trend toward orbital behavior. Though truly gaseous at the start, the molecular assemblage soon began to be seriously depleted by the escape of the more active molecules and the passage of the rest into precipitates and thence into aggregates, while these tended to lose their to-and-fro dynamics and take on circulatory, rotatory, or revolutionary dynamics.

Divergent as these trends were, they were readily reversible. When molecules escaped from a nucleus in which their habit was strictly gaseous, they usually took on a specific orbital habit and beame planetesimals; the accident of an encounter, however, might easily throw them back into to-and-fro oscillation. Notwithstanding such reversals, two quite contrasted systems of dynamics arose and were continually contending with one another in the processes that marked the passage of the nuclei into cores.

The gaseous line of descent was obviously dominant in the nuclei of the giant planets. Perhaps it was also in the nuclei of the

earth and of Venus. But just how far down the scale it held its dominance may best be left an open question for the present. The considerations about to be offered imply that the second line of evolution was preponderant in the history of the small nuclei.

In nuclei massive enough and quiescent enough to maintain high internal temperatures it seems probable that the precipitates would generally pass from the gaseous state directly into liquid droplets which would serve for a while as Brownian particles and gradually gather into liquid cores, which in turn would develop solid precipitates within themselves and ultimately collect into solid cores. In following this more typical line of gaseous descent, however, it is important to discard the old view that magmas are melts, and to replace it with the modern view, now well established, that magmas are mutual solutions. There are of course melts, and melts sometimes freeze, and so melting and freezing have some place in geological processes, but it is a rather trivial one compared with solidification by chemical processes. Even on the present surface of the earth, which for a hundred millions of years or more has been developing a temperature contrast between the exterior and the interior, simple refrigeration has little expression except in the form of thin crusts; the interiors of even surface lava flows or pools have solidified chiefly by crystallization brought about by saturation in the mutual solution. In a nucleus so conditioned as to sustain the progressive collection of a liquid core at its center by hot precipitates from enshrouding gases there is little ground for postulating even the trivial crust formation that takes place on lavas poured out on the present cold surface. Superficial refrigeration could scarcely have been more than a negligible process. Appropriate temperatures and pressures must of course have been very essential factors in core formation, but rather as imperative conditioning influences than as direct agencies. They were less intimate and ultimate factors than the chemical forces that served as the immediate actuating agencies.

Unfortunately, present knowledge of the precipitating processes deep within magmas is insufficient to predict with much confidence the history of even an ideal liquid core in a perfectly quiescent state, much less to forecast the solidification of a core actuated by

such a tortuous circulation as the case in hand seems really to involve. Inquiry should, however, at least be put on the right track by recognizing the later aspects of science and the physical realities of the case.

It is at least safe to say that isolated crystals are habitually formed *within* magmas, not merely on their surfaces. In addition to this it is particularly important to recognize that the order of formation of minerals in magmas is not that of their melting-points, but rather singularly at variance with it. Some of the minerals commonly formed earliest, as magnetite, apatite, and ziroon, are higher in specific gravity than the average minerals formed later, and these are generally higher than the liquid from which they were separated. It is quite reasonable to suppose, as leading petrologists do, that the heaviest order of minerals, at any rate, if not the majority formed, would tend to sink through the mutual solution. The actual effectiveness of this tendency must, of course, be dependent on the viscosity of the magmas, the vigor of the circulation, and other conditions. Whether the heavy minerals would remain solid and collect at once at the center or be redissolved in the depths and continue longer in the circulation is doubtless to be left an open question for the present. But this and other questions are to be considered *under the conditions of a tortuous circulation rather than those of a quiescent liquid.* The tendency of the circulation must certainly have been to equalize the temperature and to favor a slowly progressive precipitation affecting large portions, if not all of the mass, rather than the mere surface. The heavier precipitates might then rather plausibly be assumed to collect where the combined effects of current and gravity offered them the most available resting places. If so, a core shaped to fit such conditions seems more probable than a strictly symmetrical sphere.

If we turn now to the other type of nuclear evolution—in which the sifting action not only went to greater lengths, but the sifted residue was much more affected relatively by motions inherited from the expulsory action—it is well to recall at the outset that the range of cases stretches from the largest solid bodies notably affected by the sifting process downward to the very borders of

complete dispersion, such complete dispersion springing variously from inherited motions, from thermal convection, from molecular activity, or from divers combinations of these. If, as the naturalistic method insists, the solid bodies themselves are to be taken as the vestiges of the actual process, the observed range in size tallies with our previous suggestion that the limits which permit success along this line are actually reached in the existing series. Apparently our best method, then, is to consider the whole range for the sake of learning what were the inhibiting conditions at the vanishing end. We may then the better form an opinion of what probably took place nearer the middle of the great series where our interest chiefly lies. A naturalistic method is much to be preferred to a deductive treatment, for the latter is embarrassed by the multitude of possible assumptions. In pursuance of the naturalistic method let us seek some telltale feature that has been actually realized and make that our base of procedure. The series of atmosphereless bodies furnish such a base. They tell us within what bounds the inhibiting limit lay for such gases as form atmospheres. In passing through the actual conditions of evolution they have been stripped of all gases as light and active as nitrogen or oxygen. Further than this, they have maintained that condition since. The conditions must probably have been most exacting in the hot genetic stages, and there has been chance for recovery since. Their present condition, with some reservations, may be taken as an approximate indication of equilibrium conditions. The graded list in Table I giving the range of planets, planetoids, and satellites, from the earth down, may be found convenient here.

The case of atmospheric gases being thus approximately determinate, it remains to find at what stages the gases or vapors of such stony and metallic substances as make up the earth, meteorites and like bodies, would encounter their inhibitive limit. The basis for this lies in the fact that the molecular velocities of molecules vary inversely as the square roots of their molecular weights. The heavier we assume the molecules to be the more conservative our conclusions, so let us assume that the small nuclei were composed of molecules as heavy as those of the leading minerals in meteorites. The square roots of the molecular weights of the nine

minerals commonest in meteorites, including iron, are 10, 10.59, 12.49, 14.69, 15.87, 16.18, 16.49, 16.70, 18.38. These are to be compared with the square roots of representative molecules that are not held by the atmosphereless bodies. We may take the molecules of oxygen and nitrogen as representing these, the square roots of their molecular weights being 5.66 and 5.2, respectively. The high temperatures at which alone the stony and metallic substances occur in working quantities enter vitally into the case.[1] Making requisite computations, it appears that these heavier molecules would not be held under genetic conditions by the four lower orders of the bodies given in Table II. This seems to force the conclusion that the planetoids and smaller satellites were not formed in a purely gaseous way. As this is a rather radical conclusion it is well to note that the premises have not been strained to reach this result but quite the opposite. The bodies have been taken at their full present masses, whereas only their nuclei were really involved during the critical genetic stages. The molecules are taken in their present complex state, whereas in their volatile state they were quite possibly simpler and hence more active. The attractive power at the surface of the present cold concentrated bodies was used, whereas the attractions at the surface of the expanded gaseous bodies would be much lower. Other concessions to conservatism were made.

But this only excludes a direct or immediate formation by the gaseous method. It leaves open the question whether or not the cloud of precipitates into which the original mixed gaseous substances naturally passed could have completed the work. If so, the genesis might have lain in the alien line of gaseous descent, though not in that of strict gaseous formation.

It was noted earlier in the discussion that the gases of the stony and metallic substances must have begun to be precipitated soon after expulsion from the sun. In the small detached segments the precipitation must probably have gone on rather rapidly to com-

[1] I am under obligations to Dr. Fred. E. Wright, of the Geophysical Laboratory of the Carnegie Institution of Washington, for information and advice on points involved here, as also to Professor W. D. Harkins, of the University of Chicago. In the statements made I have endeavored to avoid all uncertain ground and leave everywhere a margin of safety.

pletion, and the work of aggregation into granules probably followed closely after. The conditions for the escape of the molecules that remained free would also be favored by the smallness of the bodies and the condensation of the precipitated portion. The escape of the free molecules would leave the precipitate aggregates with such internal motions as were inherited from the previous states. The last previous stage was that of a Brownian mixture whose internal motions did not differ radically from those of true gases, but the growing inelasticity must not be overlooked. The laws that would have governed the cloud of precipitates when first formed would not have differed very widely from gaseous laws. The inherited motions had, however, as we have seen, introduced a tendency toward an orbital development. In general the precipitated particles in a Brownian mixture so conditioned would not fall directly to the center even if an open path were provided for them; on the contrary they would pursue elliptical orbits about the center. By interference they would undoubtedly at length reach the center but only through a delayed course with consequent dissipation of energy.

Now the units—which at the start were perfectly elastic molecules—would by the precipitating and aggregating processes grow into granules many million times more massive, and in the process would become increasingly inelastic. By this change in the nature of the unit there would have arisen a wide gap between even the heaviest of the free molecules and the average spherules, granules, or chondrules into which the precipitates passed. The velocities of the latter would have been of so much lower order that there seem no good grounds to doubt that the main mass of the latter would be susceptible of control and continued concentration under conditions that would be quite prohibitive of control as free molecules.

The very process of molecular escape tended in itself to increase the gap between the units prone to escape and those prone to continue their concentration. In every collision from which a molecule escapes by rebound there is an equal reaction of the partner in collision in the opposite direction. The escaping molecule usually has the lesser mass and to give escape the rebound must

be outward; the reacting molecule or granule therefore rebounds inward. *The very process of dispersion was therefore mated with a concentrating process and the two divided their results between the forming of nuclei on the one hand and of planetesimals on the other.* On the residual side of the twin process the ultimate result was the formation of a cloud of precipitated granules from which all free molecules had escaped. The cloud of course had less mass than the previous mixed nucleus, but there was a proportionately larger reduction of dispersive activity.

In the light of this we need next to consider further the holding power represented by the spheres of control. The spheres of control in Table II are computed for the earth's distance from the sun. They would be relatively larger farther out and smaller farther in. By reference to the table it will be seen that the fields under control are by no means insignificant even for the smallest bodies represented. At the same time, reference to the adjoining columns of the table will show that the *strength* of control is distinctly limited. It is also to be noted that the velocities of retention and escape are given for the surfaces of the concentrated bodies as these now are, and that the velocities that can be controlled decline rapidly for points farther from the center.

Now expansion does not affect the simple static holding power so much as it does the velocity that can be controlled. Within the limits of the sphere of control, and with some other qualifications, simple expansion or contraction does not affect the extent of the sphere of control. It is a principle of celestial mechanics that if a body is spherical and if its substance is distributed either uniformly or in homogeneous concentric layers its gravitative effect on bodies outside it is as though the whole matter were concentrated at the center, and hence, of course, expansion or contraction is immaterial so far as relates to bodies on the borders and outside the body itself. If the body is not strictly spherical or homogeneous in concentric layers, the deduction will not strictly hold, but any departure will in general be measurably in proportion to the departure from sphericity or homogeneity, so that the principle may be used without radical error in respect to normal spheroids of revolution. Applying this deduction to the range of bodies rep-

resented in Table II, the sizes of the spheres of control will remain about as given whether the substance they contain takes the form of an expanded gas, or an open swarm of precipitated granules, or a compact solid body. This puts everyone in the way of modifying at pleasure the illustrations I offer.

To the concrete pictures already given the following may be added as now more immediately serviceable. From the minimum radius of the sphere of control of the earth, 620,000 miles, let a depth of 20,000 miles on the outer border be left essentially unoccupied and the whole present substance of the earth distributed uniformly throughout the remainder. It would have a density of 0.001266 on the air standard. In the form of a cloud of granules, each half the mean density of the earth, and distributed uniformly, the empty space about each granule would be over a million and a half times the space occupied by the granule itself.

If a 10-mile planetoid were converted into a cloud of granules uniformly distributed through its sphere of control, the cloud would have a density of 0.00111 on the air standard. If the granules had the same density as in the planetoid, the average empty space about each granule would be more than two million times the volume of the granule itself.

If therefore the clouds of granules were quite diffuse, they yet might be controlled by their mutual gravity, *provided* the dispersive components of their internal movements were negligible. But with such wide distribution any appreciable dispersive movements would be fatal to control.

To fashion a case of this order with a working margin of space, let the matter of a 10-mile planetoid of density 3.3 be dispersed uniformly as granules of like density throughout the central $\frac{1}{8}$ of its sphere of control, leaving the remaining $\frac{7}{8}$ as empty space which the granules must cross to escape. The density on the air standard would be 0.00889, while the average empty space surrounding each granule would be 280,000 times the volume of the granule itself. Even in this case the velocity at the surface that would give escape if directed outward would be perilously low, not above a fraction of an inch per second. This reveals the critical nature of all this class of cases. To insure success in final concentration, the

sifting process that preceded must have removed all constituents whose motions had any notable dispersing component; nor can any such component arise from mutual interaction without jeopardy. Almost the only line along which a body so small as a 10-mile planetoid could organize itself by the granular method seems to have lain in acquiring very early a higher central density and a less outward extension than that assigned. This might perhaps have been done by the reaction above noted. The peril of dispersion and the narrow margin of control in such cases lead to the conclusion that the smallest order of planetoids and satellites lie near—or perhaps quite on—the limit of possible genesis by even this divergent phase of the gaseous line of descent.

This conclusion tallies with the fact that no planetoids or satellites of the smaller order are known at the earth's distance from the sun, or within it. Bodies of this type appear only at the distance of Mars and beyond. The dynamic conditions of this inner region are perhaps too adverse for this type of formation. In the outer region conditions are notably less restrictive, but even there they undoubtedly put lower limits on the size of bodies formed by the gaseo-granular method of assemblage.

In the light of these considerations there seems little warrant for supposing that such bodies were ever formed in sufficiently great multitudes to have built up the earth or to have pitted the surface of the moon by their impacts. The number of lunar craters is estimated at 30,000. If each of these is the grave of an extinct planetoid, one might expect that a few living ones would have lingered to tell the story. The negative testimony of the heavens as to their existence in this region seems rather to favor the view that their restriction to the outer region implies that they are themselves witnesses to the limitation of this line of genesis in both place and frequency.

With the general lines and limits of nuclear evolution thus defined, our remaining task is to find the median places between the two extremes that fit the earth, Venus, Mars, and the moon. It is clear from the present state of these bodies that much sifting of the original solar gases was required, for while the earth, Venus, and Mars hold envelopes of gases of moderate molecular weight,

they do not hold hydrogen and helium, which abound in the sun in appreciable quantities. The sum total of the gases they do hold relative to the whole mass of these planets is very small. Even in the case of the earth, distinctly the most massive of the solid bodies, the sifting must have gone to very notable lengths.

It is not impossible that the nuclei of all four bodies were so far sifted down as to exclude essentially all the atmospheric gases, and as a result their concentration fell ultimately into the precipitate line of descent. On the other hand, it is quite possible that the earth and Venus had atmospheres of some moment at all stages. In the case of the moon, there seems no escape from the view that its nucleus could not have formed in gaseous fashion, for the moon does not even now hold an atmosphere. In its original hot diffuse state a mass of so low an order as the nucleus of the moon could only hold its material in the precipitate form. The atmosphere of the adult Mars is so scant that its nucleus probably had no appreciable atmosphere. It is doubtful whether Mars could even now, in its full-grown state, hold the atmosphere it has if the planet were heated to the point of volatilizing its stony substances. The cases of Venus and the earth seem so nearly on the border line that it is not unreasonable to take either view as the evidence now stands. Further study may turn the scales one way or the other.

So far as the shrinkage question is concerned, the matter narrows down to the possibility that the nuclei of the earth and Venus passed from their original gaseous states into planetary cores along the normal line of gaseous descent. If the main mass of the nucleus of the earth passed from the solar gaseous state into a central liquid magma and thence by chemico-crystalline action into a solid core, the process would have given special facilities for the adjustment of the matter in the interest of density. To that extent it would have forestalled later shrinkage that might otherwise have been recorded in diastrophic features. The *record* would not cover the full reality. The large amount of shrinkage deduced by our comparison of the moon, Mars, Venus, and the earth[1] would not be recorded even in the basal features of the earth's configuration. These studies, however, imply that the unrecorded

[1] *Jour. Geol.*, Vol. XXVIII (1920), pp. 1–17.

factor was not necessarily large relatively, even if the gaseo-molten phase of nuclear history did obtain and is given as generous an estimate as the data will warrant.

It ought not to be overlooked, however, that the solid core, in its assigned formation by the deposition of crystals or other precipitates from the gyrating currents of the central circulation, would have been very likely to have incorporated inequalities of material and taken on asymmetries of form so as to have presented a deformed foundation, as it were, for the later accretions. Such deformities would have been likely to have made themselves felt in the diastrophism of all that was built upon them. This is a phase of the subject which I hope to pursue further in the future.

IV. EXTERIOR AGENCIES THAT AFFECTED THE PLANETARY CORES DURING THEIR FORMATION AND AFTERWARD

The discussion thus far has been confined to agencies acting within the evolving masses. The evolution, however, was not free from influences that acted from without. One type of such action particularly requires consideration here, because it affected the successive adjustments and readjustments of material in the planetary cores. It will suffice to consider merely the case of the earth and the most typical agencies that affected it. The three agencies that lie back of changes of rotation, of nutation, and of the tides will sufficiently represent the whole. These agencies—and those of their kind here neglected—arose out of the same general processes as the planetary series itself and came gradually into function as the planets themselves took form. They were more or less effective at all stages thereafter. One special effect was to bring into play the resources that lay in the *mass-coherence* of solids, an essentially new element in the evolution.

The forces that produced the tides, the polar nutations and the changes in rate of rotation, not only caused changes of form that involved variations in the internal capacity of such inclosed spaces as there may have been, but caused differential stresses to permeate the growing cores from surface to center and call into action the viselike capabilities of stresses greater below than above. Those agencies which give rise to deformations of the

class known as zonal harmonics of the second order, such as the bulging of an equator and flattening of the poles, or the pulling out of polar cones and the flattening of the equatorial belt between, give rise to stresses much greater in the central parts than in the outer parts. Sir George Darwin[1] and others have computed these for an incompressible homogeneous earth and for certain compressible variations from this. In an incompressible homogeneous earth Darwin gives the differential stresses as bearing the ratios 8 at the center, 3 at the equatorial surface, and 1 at the poles. In a compressible earth the surficial stresses are relatively lower and those at the center relatively higher. For a certain compressibility the surficial stresses disappear and the central stresses rise $\frac{1}{6}$ in value.[2]

Now the main tidal stresses come and go every twelve hours and the subordinate tidal stresses at other and generally longer intervals. While relatively small, they are constantly acting in a given direction, and this presumably has a certain kind of cumulative effect. This effect is doubtless chiefly felt by such molecules of the interior as are under stress and are about ready to change their attachments and so are responsive to the influence of even small strains. It is coming to be recognized that such individual molecular activities constitute a notable factor in rock metamorphism, glacial motion, and other geological changes of a very intimate sort. This has been set forth by Leith[3] and other close students of the intimate nature of geological phenomena. Such persistent rhythmical oscillations of stress and strain as those of the tides seem well suited to aid effectually these individual molecular changes. The nutations of the poles represent pulsatory action whose periods are longer, but whose chief effects are probably of the same intimate sort.

Changes of rotation, however, represent action of a much higher order of power and much greater length of period. In deformative potency, rotation has a competency of the first order. Changes of rate of rotation were probably most active and effective while

[1] *Scientific Papers*, by Sir George Darwin, Vol. II (1908), pp. 476–81.

[2] *Ibid.*, p. 505.

[3] Leith and Mead, *Metamorphic Geology* (1905), pp. 173–76, and elsewhere.

planetesimal accretion was in progress. The earth core was then youngest and least compressed, and so probably least rigid and most susceptible to the influence of differential stresses. I have elsewhere shown that the changes in rotation were probably oscillatory about a medial rate in conformity to a law of equilibrium.[1] They may be regarded therefore as commanding influences both in respect to power and to the times and modes of application.

The elevated poles and depressed equator of the rhythmical tidal deformations were transverse to the elevated equator and depressed poles of the rotational changes, and this transverse attitude no doubt lent facility to the kneading action which their rhythmical periods brought to bear on the interior of the earth.

These co-operating agencies thus brought to bear on the whole interior of the solidifying earth a rhythmical series of differential stresses, most intense in the deeper parts and less intense toward the surface, and so admirably fitted to force the mobile and the lighter material toward the surface and to favor readjustments that brought about increased density and rigidity and probably also increased elasticity. It seems to me probable that this combination of strong mechanical stresses at distant intervals working with much gentler and more rapid rhythmical stresses has been the master-factor in controlling the secular reorganization of the earth's interior, a gradual reorganization which I think has been in progress from the time solidification began down to the present day. The normal result, as I see it, would be a general gradation of concentrative effects from surface to center—taking form in appropriate gradations of density, rigidity, and elasticity, also graded from surface to center. The results of our comparative study of the earth, moon, Mars, and Venus tally perfectly with this view and make it theoretically logical and consistent. The steadily increasing density from smaller body to larger body, in spite of the high probability that the smaller bodies inherited the heavier molecules, points very definitely to reorganization under the influence of compression. The oscillating differential stresses, greater below than above, seem peculiarly well suited to aid in working out the graded adjustments.

[1] *The Origin of the Earth* (1916), pp. 95–110, 172–79.

The cumulative evidences of recent investigations on tidal, seismic, nutational, and other phenomena support this view with little less than demonstrative effect. The most of these are now quite familiar. There is space here merely to quote the latest numerical determinations (1917) that have come to my notice. Schweydar,[1] as the result of observational, experimental, and mathematical work on the tides, the polar nutations, and the transmission of seismic waves, concludes that the earth conducts itself as though it had a mean rigidity $2\frac{1}{2}$ times that of steel, that the constant of rigidity at the surface is about 3×10^{11} dynes, that this increases in depth more rapidly than the density, so that at the center it reaches 30×10^{11} dynes, or ten times its value at the surface. The transverse seismic waves, as far down as the record permits a confident interpretation, indicate a definite gradation of density, rigidity, and elasticity. To insure that the total rigidity shall reach the mean value of $2\frac{1}{2}$ times steel, and at the same time be consistent with the rigidity known to prevail in the outer zone and the gradually rising rigidity implied by seismic waves as far down as their record is good, it seems clear that a high order of rigidity in the remaining central part is imperative. The old hypothesis of an iron core framed, among other reasons, to account for the high mean density of the earth—a purpose which it serves only clumsily—does not help much in meeting the still higher rate of rise of rigidity and elasticity toward the center, for iron is soft and malleable when hot. Nor does any special segregation of inherently heavy material in the earth, however helpful it may be in its place, fully satisfy the phenomena brought out by the comparative studies on the earth, the moon, Mars, and Venus. The whole evidence seems to point clearly to a systematic mass-effect, working on essentially the same material in all cases, aided, to be sure, but aided in only minor degree, by selective segregation. In the heart of the earth very likely the segregation of the metallic from the stony material has gone much farther than in the outer parts, but I see little reason to think the two classes of material have been wholly separated from one another. A segregation

[1] W. Schweydar, "Ueber die Elastizität der Erde," Sonderabdruck aus *Die Naturwissenschaften* (1917), pp. 1–27.

of the iron and allied metals into masses of moderate dimensions distributed through the stony material, after the fashion of the metallic and stony material in meteorites, would probably affect appreciably the transmission of transverse seismic waves, and so account for the peculiarities of the record of such waves as come through the heart of the earth quite as well as the assumption of a purely metallic core. An original mixed constitution from center to surface kneaded into the present solidity by differential stresses whose central intensity is to their surface intensity in about the same ratio as the central density, rigidity, and elasticity is to the surface density, rigidity, and elasticity seems to fit the requirements of the case.